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TO: G.W. Jackson
Manager, Telecommunications
Design & Development Div - Transmission
H10A19

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OTTAWA RIVERDALE TS - GROUNDING SYSTEM STUDIES

P. Pillai

Tests were conducted at Ottawa Riverdale TS under simulated fault conditions in order to evaluate the adequacy of the grounding system performance at the station and the protection of communication circuits. The station ground potential rise and touch and step potentials were found well under safe limits, for an ultimate HV fault current of 11 kA. The measured induction on the communication line paralleling the faulted power line was very small. Models were developed to generalize the results. Soil resistivity at the station was also tested.

1.0 INTRODUCTION

Ottawa Riverdale TS is located in an older residential part of Ottawa at the corner of Main Street and Riverdale Ave. Three 115 kV overhead lines (circuits K1R, A3RM and H2AR) supply three transformer banks at the station, each bank with three single phase transformers rated 5000 kVA, 63.5/11 kV, Yg/Δ. Pipe-type cables to Slater TS are also terminated to each of these HV circuits at the station. The station supplies Ottawa Hydro Electric System (OHES) loads through fifteen 11 kV and ten 4 kV feeders installed in underground duct systems. The station is characterized by an irregular ground grid mesh. Also the area is probably congested with other underground services interconnected to an extensive network of multigrounded distribution neutrals connected to the station ground. This makes design-type calculations of the grounding system performance at the station complicated. Therefore, tests were conducted under simulated fault conditions to determine the grounding system performance at the station and induction on communication lines paralleling the faulted power lines. The objectives of the test were to confirm the adequacy of the existing grounding system performance at the station with respect to public safety, station security and protection of communication cables and to develop models to generalize the results. The project was requested and funded by Design and Development Division - Transmission.

job	file	date	report no.
18-146-404	813.521	May 22, 1987	87-89-K

2.0 TEST PROCEDURE

Simulated fault current tests were conducted on June 17 and 18, 1986 at Riverdale TS to measure the station grounding system performance. The 115 kV circuit K1R between Riverdale TS and Overbrook TS was taken out of service and the line grounding switch at Overbrook TS was closed to sink test current. A test current of 25A at 120 V, 66 Hz from a gasoline-powered generator was injected into three parallel phases of the remotely grounded test circuit as shown in Figure 1. The following measurements were made:

(a) Station ground potential rise between a remotely grounded communication cable (to OHES Queens sub) and local station ground. Only a modest potential profile measurement was feasible since the station is surrounded by busy streets.

(b) Induction on an Ontario Hydro communication cable on a wood pole line between Queens Sub and Walkley Junction which parallels the test circuit with an estimated separation distance of 9 m.

(c) Touch potentials at the station.

(d) Current splits on skywires, HV cable sheaths, distribution neutrals, communication cable sheaths and water pipe.

(e) Soil resistivity tests.

Figure 2 gives a layout of the station with respect to the grounding tests. Here, the distribution neutrals are assumed to be in three directions. Potentials and currents were recorded with respect to $1.0\underline{/0}$ A injected current. A Solartron 1170 frequency network analyzer synchronized to the 66 Hz generator and capable of rejecting 60 Hz noise level was used in conjunction with a 6-channel amplifier to measure the ratio of two inputs including phase angle. A portable 2-channel oscilloscope was used to check the interference level. Two Ritz clip-on 5 VA, 150:5 A CTs with 0.66 Ω shunts were used to supply the Solartron reference signal and to measure current splits in various conductors. A large split core Annis CT of 2000:5 A ratio with 10 Ω shunt was used to measure current splits on the large distribution cable sheaths. A patch panel allowed switching of test leads between teams measuring potentials and currents. Telephone style carbon protectors were used to limit the potential to local ground on the input wiring to the instrumentation in the event of a system fault. Heavy connections were made from the frame of the instrumentation to the truck body and station ground for personnel safety.

The Wenner method using a Megger DET-2 ground resistance tester was used to determine the soil resistivity at the station. Resistivity surveys were done on the north and south fields inside the station property.

Assistance was obtained from Regional and District Operations, Station and Lines Maintenance, District P&C, Head Office and Ottawa Hydro staff in applying for the above outage, making temporary connections to the isolated HV line, locating the various cable sheaths and communication pairs and in conducting the measurements.

3.0 TEST RESULTS

3.1 Measured Soil Resistivity

The soil was moist due to rain on the previous day. Table 1 shows the apparent resistivities calculated from the average of the two surveys using equation 7.1 of the Grounding Guide/1/. An equivalent two-layer soil model was fitted to the test data and gave a top layer of 6.4 m in thickness with a resistivity of 300 Ω.m and a lower layer having a resistivity of 37.5 Ω.m.

3.2 Measured Ground Potential Rise

The station ground potential rise of 43.00 /-14 mV/A, measured using a remotely grounded communication cable to Queens Sub, was corrected to take into account an estimated shielding factor of about 0.9/-22 for the communication cable. An additional correction factor of 27.8/71 mV/A was applied to compensate for mutual coupling between the communication cable and distribution neutrals going south along Main Street. Here, an exposure length of 500 m and a separation distance of 5 m were assumed. Also equal current distribution was assumed on the feeder neutrals in each of the three directions. The corrected measured GPR is 78.2/26 mV/A which is about 860/26 V for an ultimate HV station fault current of 11 kA.

3.3 Measured Induction on Communication Cable

The communication cable between Queens Sub and Walkley Junction parallels the 115 kV test circuit K1R for 1.4 km as scaled from the drawing showing Ontario Hydro lines in the City of Ottawa. A modest induced voltage of 1.74 /-87 mV/A (without GPR) was measured on this communication cable due to the injected test current on the line K1R.

3.4 Measured Touch Potentials

The measured station touch (mesh) and fence touch potentials are given in Table 2. The fence touch potential measurements were repeated at several locations at the station and the average value is presented in the table. For an ultimate HV station fault current of 11 kA, the measured station touch and fence touch potentials are 12 /43 V and 52 /55 V respectively. Potentials of 1.33 /50 mV/A and 13.0/45 mV/A were measured respectively between the station fence and the station ground grid and between the station fence and the fence around the SC2 capacitor bank located at south west corner of the station.

TABLE 1

Riverdale TS
Measured and Model Fitted Soil Resistivities

Probe Spacing (m)	Measured Apparent Resistivities (Ω.m)	
	North Field	South Field
1	188.8	286.5
2	235.5	310.9
5	214.8	336.9
10	112.4	175.2
20	44.6	69.6

TABLE 2

Riverdale TS
Measured and Modelled Potentials
For a HV Station Fault at Riverdale TS

	Measured (mV/A)	Modelled (mV/A)
Ground Potential Rise	78.2 /26	84.0 /49
Induction on Comm. Cable	1.74 /-87	23.1 /66
Station Touch (mesh) Potential	1.13 /43	18.8 /49
Station Step Potential	-	9.36 /49
Fence Outside Touch Potential	4.74 /55	22.9 /49

3.5 Measured Current Splits

Table 3 gives the measured current splits along with the modelled values. The distribution neutral split includes those measured on the feeder cable sheaths and bonding wires inside the control building. The skywire splits were measured at the north and south insulator structures inside the station. The measured splits on the skywires and the distribution neutrals are considerably lower than the modelled values. Perhaps we did not see all of the splits. Therefore, the component of the station ground current presented in Table 3 under measurement was estimated from the measured GPR and calculated R_g.

TABLE 3

Riverdale TS
Measured and Modelled Current Splits

Current Path	Measured (A)	Modelled (A)
Injected to K1R phases	1.00 /0	1.00 /0
Skywires	0.153 /21	0.456 /24
HV pipes	0.073 /17	0.067 /-34
Distribution Neutrals	0.252 /18	0.385 /-31
Water pipe	0.127 /0	+ 0.127 /0
Communication Cable Sheaths	0.030 /2	+ 0.030 /2
Station ground	*0.070 /-26	0.075 /49
Total Split	0.700 /15	1.00 /0

* Estimated as (Measure GPR/Calculated R_g)
\+ Measured Values used in the model.

4.0 MODELLED RESULTS

Appendix A summarizes the various formulas used in the calculations other than those listed in the Grounding Guide/1/ and IEEE Guide 80/2/.

4.1 Soil Resistivity

The measured soil resistivity data was interpreted as a two-layer soil model using the method given in Appendix D of the Grounding Guide/1/. The model is based on the average of the two surveys. An equivalent soil resistivity of 174 Ω.m was obtained from the two layer model for an estimated equivalent station radius of 43.7 m.

4.2 Isolated Station Ground Resistance

The calculated station ground resistance, R_g at Riverdale TS is 1.12 Ω, based on an estimated equivalent station radius of 43.7 m and 1450 m of buried ground conductors (Equation 3.3 of the Grounding Guide/1/).

4.3 Conductive Equivalent Circuit

Figure 3 shows the grounding system interconnections at Riverdale TS with respect to fault current splits and Figure 4 shows the conductive equivalent circuit for test conditions. The conductive circuit impedances, Z_c were calculated using simplified formulas for Carson's earth return self impedances which carry the conductive component of the fault current/3/.

For the two 117 mm^2 aluminum-clad skywires, an equivalent conductor earth return self impedance was calculated as 0.75 /55 Ω/km based on an equivalent geometric mean radius of 0.28 m for the two skywires. Assuming a tower footing radius of 2 m and footing spacing of 10 m the calculated tower footing resistance is 12 Ω. From the ladder network of the skywire self impedance and the tower footing resistance, the lumped conductive impedance, Z_{c1} of the skywire system is 1.50 /23 Ω for a tower span length of 250 m. A shielding factor, S of 0.66/-14 was calculated from the skywire self and mutual impedances which is the component of the fault current applied to the conductive equivalent circuit. The inductive component of the skywire current calculated as (1-S) I_f is 0.40 /24 A.

The conductive circuit impedances of the HV cable pipes include Carson's earth return and internal ac impedances. Calculation details are given in/3/. The pipe type cable circuits K1R and H2AR are run in parallel with approximately 1 m separation. For the three pipe circuits, the parallel circuit impedance was calculated as 1.27 /83 Ω including the mutual effect. At Slater TS, with extensive distribution neutrals, the station ground impedance should be very small and was neglected compared to the pipe impedance.

For the twenty-five OHES distribution feeders installed in ducts, a net impedance Z_{c3} of 0.22 /80 Ω was calculated based on the parallel combination of the feeders grouped in three directions. Here, a GMR of 0.2 m in the ducts/4/ and an average length of about 1000 m to the nearest grounding point (estimated from distribution system drawings) were assumed. This model is different from that at Overbrook TS where the feeder cables are grouped either in ducts or direct buried inside the station and they are carried on overhead poles outside the station/5/. For an HV fault, the ground resistance of the OHES distribution station was neglected.

Current splits of 0.127/0 A and 0.030/2 A were measured on the water pipe and communication cable sheaths respectively. However, due to lack of data and complexity of calculations involved, no attempt was made to model the water pipe and communication cable sheaths. Instead the measured splits were assumed in the model.

From the network of Figure 4, the resulting interconnected station ground impedance is 0.17 /67 Ω.

4.4 Modelled Current Splits

The conductive equivalent circuit in Figure 4 was solved for an injected station fault current of 1.00 /0 A. The calculated current splits are given in Table 3. Note that the skywire current is the sum of conductive and inductive components.

4.5 Modelled Ground Potential Rise

From the resulting station ground current split I_g, the ground potential rise V_g at Riverdale TS was calculated as $I_g R_g$ where R_g is the isolated station ground resistance. Table 2 compares the modelled value with the measured result. For an ultimate HV fault level of 11 kA, the calculated GPR is about 924 /49 V.

Preliminary calculations were also done to estimate the station GPR in the event of a LV fault on a single 11 kV OHES distribution station (DS). For this purpose, the entire fault current injected at the DS was assumed to be supplied from Riverdale TS. Assuming that the fault is fed through a 3-conductor, 500 MCM, PILC, belted cable with the sheath bonded at the DS and a 1000 m fault distance, the calculated GPR at Riverdale TS is approximately 820 /26 V for a LV (11 kV) fault level of 16.5 kA. Here, a shielding factor of 0.44 /-57 was calculated for the cable assuming a lead sheath of thickness 3.2 mm. A grounding resistance of 0.5 Ω was assumed at the fault location. Alternately, for a 107 mm^2 (4/0) copper bonding wire instead of the cable sheath, the GPR at Riverdale TS would be about 760 /72 V for the above LV fault current. However, there is a possibility that all the distribution cables may not be bonded at the far end as noticed at a few poles at some other Ottawa stations. Therefore, assuming a worst case with no bonding of the distribution feeders and no return current in the cable shields and also neglecting the ground resistance at the fault location, the GPR at Riverdale TS could be about 2.8 /67 kV for the above LV fault level.

4.6 Modelled Station Touch and Step Potentials

The station touch (mesh) and step potentials were calculated using Equation (3.6) of the Grounding Guide/1/ and Equation (75) of IEEE Guide 80/2/ respectively and are given in Table 2. For an ultimate HV fault current of 11 kA, the calculated station touch and step voltages are 207 /49 V and 103 /49 V respectively.

4.7 Modelled Fence Touch Potential

Touch voltage to the public outside the fence was calculated using equation (3.10) of the Grounding Guide/1/ and is given in Table 2 along with measured result. This is about 252 /49 V for an ultimate HV fault current of 11 kA. Table 2 compares the modelled value with the measured result.

4.8 Modelled Induction

Induction on the communication cable paralleling the test circuit K1R was calculated using Carson's simplified formula for earth return mutual impedance. This preliminary calculation gives an induced voltage of about 231 /66 mV/A, for an exposure length of 1.4 km and a spacing of 9 m. A shielding factor of 0.7 was assumed for the communication cable. A detailed modelling was not attempted due to lack of data and complexities involved such as the current splits on the underground service connections and distribution neutrals on the poles carrying the communication cable, shielding of the cable and messenger wire etc.

5.0 DISCUSSION OF RESULTS

5.1 The extensive multigrounded distribution system is the most significant factor in reducing the station ground impedance to 0.17 /67 Ω. The calculated isolated station ground resistance is 1.12 Ω.

5.2 As a result of the above, the ground potential rise at the station is considerably reduced and is well under the recommended limit of 3 kV for an ultimate HV fault current of 11 kA. The estimated correction factor of 27.84/71 mV/A which was added to the measured value to compensate for the mutual coupling (Section 3.2) should be conservative. The corrected measured result compares reasonably with the modelled value (Table 2).

5.3 Preliminary calculations indicated that the GPR at Riverdale TS for a LV (11 kV) fault current of 16.5 kA fed through a bonded distribution cable is comparable to the GPR for the above HV fault level. Therefore, a detailed modelling for a LV fault was not considered necessary at this time. However, assuming that the distribution cable supplying the fault current is not continuously bonded at the fault location, the station GPR tends to approach the recommended limit of 3 kV. In this case, the station touch potentials could also exceed the tolerable limit.

5.4 The considerably lower measured current split on the LV distribution neutrals indicates the possibility that a few measurements were missed in the field. Also the measured skywire current split is only about 34% of the modelled value. Perhaps there could be some inadvertent connections of the skywires to the HV towers at the station. On the other hand, assuming that the measurement is good, the lower measured split may be due to poor bonding of the skywires. Due to these uncertainties, deriving station ground resistance, R_g, from measured current splits is not recommended. However, for stations with extensive network of LV distribution cables, an accurate estimate of R_g may not be necessary for grounding system design. The distribution neutrals should be considered in detail in such cases to derive station ground potential rise.

5.5 Heavy skywires at the station provides effective shielding. Only about 66% of fault current enters the station grounding system which includes the various conductive current paths as shown in Figure 3.

5.6 About 13% of the station fault current was measured on the water pipe leaving the station and this could result in undesirable transfer of potentials outside the station. It is possible that the pipe does not include an insulated section.

5.7 A longitudinal induced voltage of about 1.74 /-87 mV/A was measured on the communication cable paralleling the test circuit. Preliminary modelling shows a much larger value. Research is needed to develop a model, validated by field measurements, to determine induced voltages on communication cable paralleled by HV circuits under fault conditions.

5.8 The tolerable limits of touch and step potentials calculated using Equation (2.4) and (2.2) of the Grounding Guide/1/ are 206 V and 337 V respectively for bare soil surface. The measured station touch and fence touch (highest of the several measured) potentials of approximately 12 /43 V and 118 /50 V respectively for a fault current of 11 kA are both under the tolerable touch voltage limit but the modelled values exceed the limit. The modelled results may be conservative with respect to the tolerable limits since the extended grounding system provided by the distribution neutrals which tends to reduce gradients was not considered in the calculations.

5.9 The relatively small voltage measured between the station fence and the station ground grid indicates that the fence is grounded to the grid as shown in the design drawings.

6.0 CONCLUSIONS

6.1 The equivalent soil resistivity at Riverdale TS for an estimated station radius of 44 m is about 174 Ω.m based on a two-layer soil model obtained from Wenner test data.

6.2 The isolated station ground resistance calculated from the ground grid geometry is 1.12 Ω. The interconnected station ground impedance is 0.17 /67 Ω, mainly due to the parallel combination of the several interconnected distribution neutrals.

6.3 The ground potential rise (GPR) at Riverdale TS as measured using a communication cable is about 860 /26 V for an ultimate station fault current of 11 kA on the HV circuit K1R. This includes an estimated correction factor of about 36% to account for mutual coupling between potential and current leads. The modelled value is about 924 /49 V for the above fault current. Preliminary calculations gave a station GPR of about 820 /26 V for a LV (11 kV) fault current of 16.5 kA supplied through a bonded distribution cable. The ground potential rise at the station is well under the recommended limit of 3 kV. However, preliminary calculations indicated that if a feeder cable is not bonded at a pole or a DS and a fault occurs at this location, the GPR at Riverdale TS tends to approach the recommended limit.

6.4 For stations with extensive LV feeder cables, the distribution neutrals are more important than the station ground resistance in deriving the ground potential rise. Preliminary models have been developed to estimate the station ground potential rise.

6.5 Measurements showed that the station fence is interconnected to the main station ground grid and the fence around the SC2 capacitor bank is isolated as shown in the station design drawings.

6.6 The measured station mesh voltage and fence touch potential to the public outside the station for an ultimate HV fault current of 11 kA are both within the tolerable touch voltage limit calculated for the station. However, the modelled results exceed the limit, but the model is based on conservative assumptions. The calculated station step potential for the above fault current is under the tolerable limit.

6.7 Heavy skywires at the station provide an effective shielding of about 66%.

6.8 A longitudinal induction of about 1.74 /-87 mV/A was measured on the communication cable between Queen's Sub and Walkley Jct which parallels the test circuit K1R. This is about 19 /-87 V for a fault current of 11 kA on the circuit K1R. The exposure length is approximately 1.4 km.

6.9 A split of about 13% of the station fault current was measured on the water pipe leaving the station.

7.0 RECOMMENDATIONS

7.1 In view of the relatively lower measured skywire current split compared to the calculated value, the skywire connections should be checked to ensure proper bonding.

7.2 The water pipe connections leaving the station should be checked and insulated section or equivalent should be provided if needed.

7.3 Distribution neutrals should be considered in detail in the design of grounding systems for stations with extensive interconnected distribution feeders. Preliminary models have been developed for this purpose and are being reviewed by Electrical Research Department.

7.4 Ontario Hydro, in consultation with Ottawa Hydro Electric System, should consider checking the distribution cables leaving the station for proper bonding in order to reduce the station GPR under LV fault conditions.

Approved:

A.F. Baljet
Manager
Electrical Research Department

Submitted:

R.P. Pillai
Engineer
System Studies Section
Electrical Research Department

RPP:td

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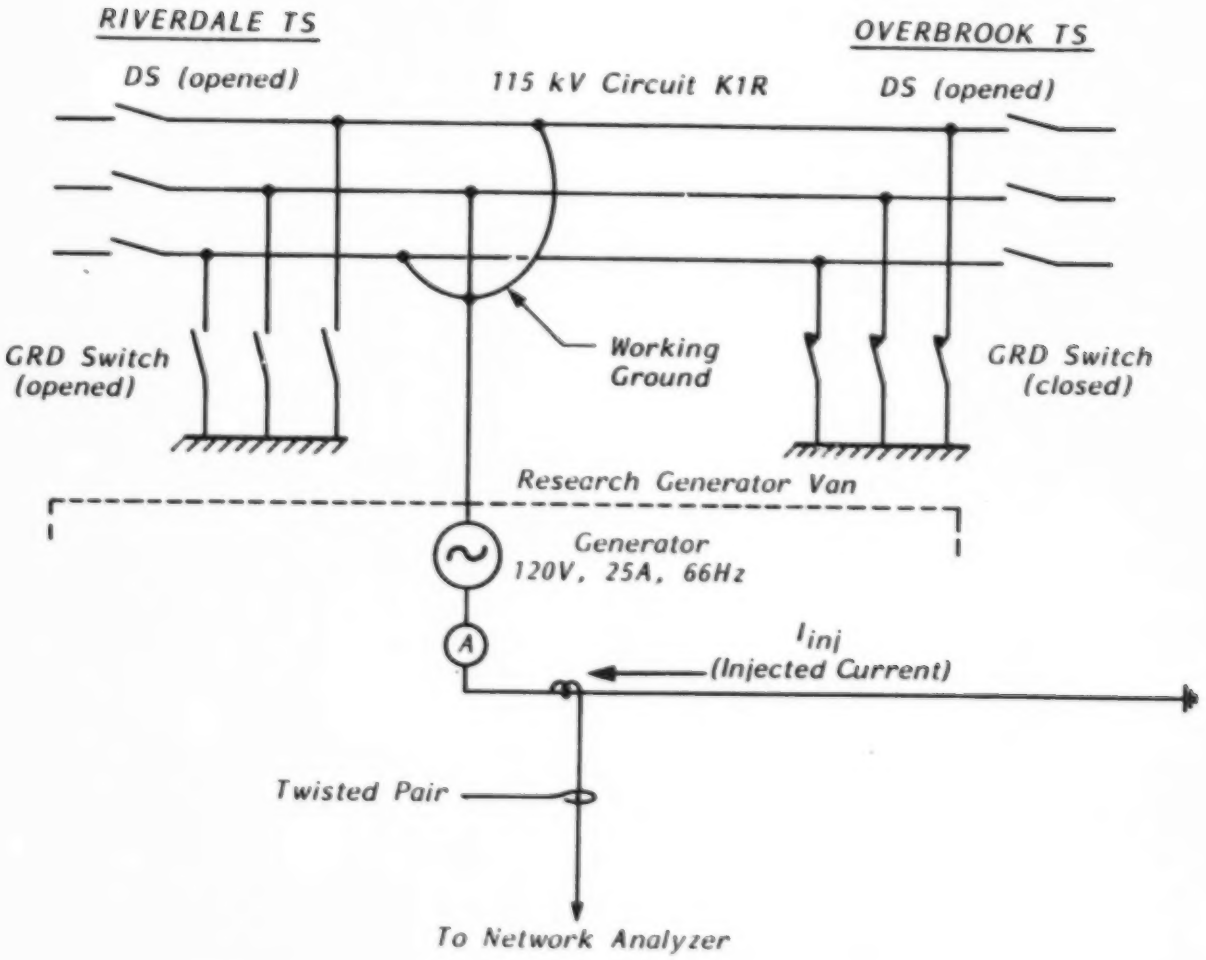

FIGURE 1 -
OTTAWA RIVERDALE TS
GROUNDING TESTS - FAULT SIMULATION CIRCUIT

174393-RD

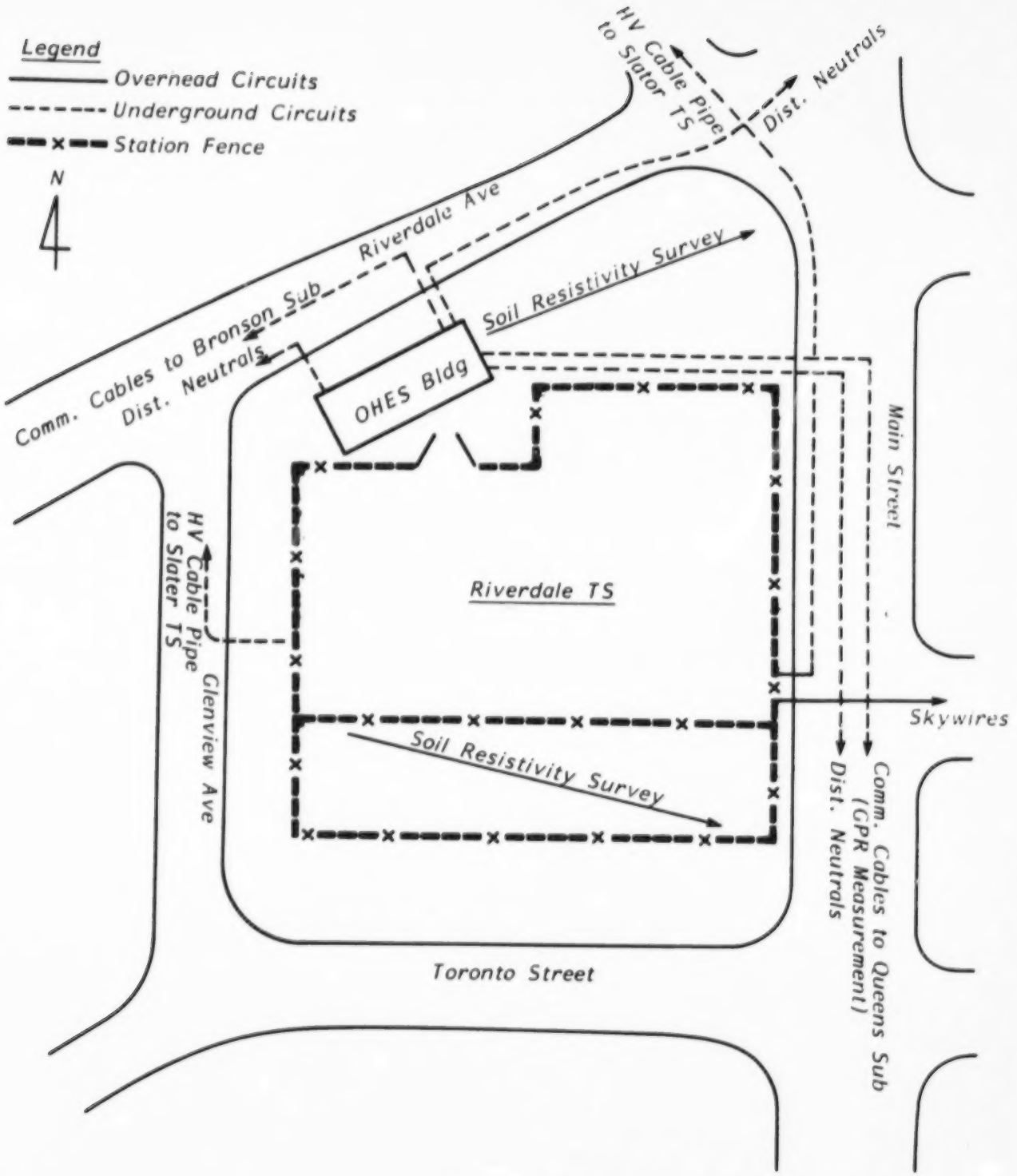

FIGURE 2

OTTAWA RIVERDALE TS
LAYOUT WITH RESPECT TO GROUNDING TESTS
(NOT TO SCALE)

174618-RD

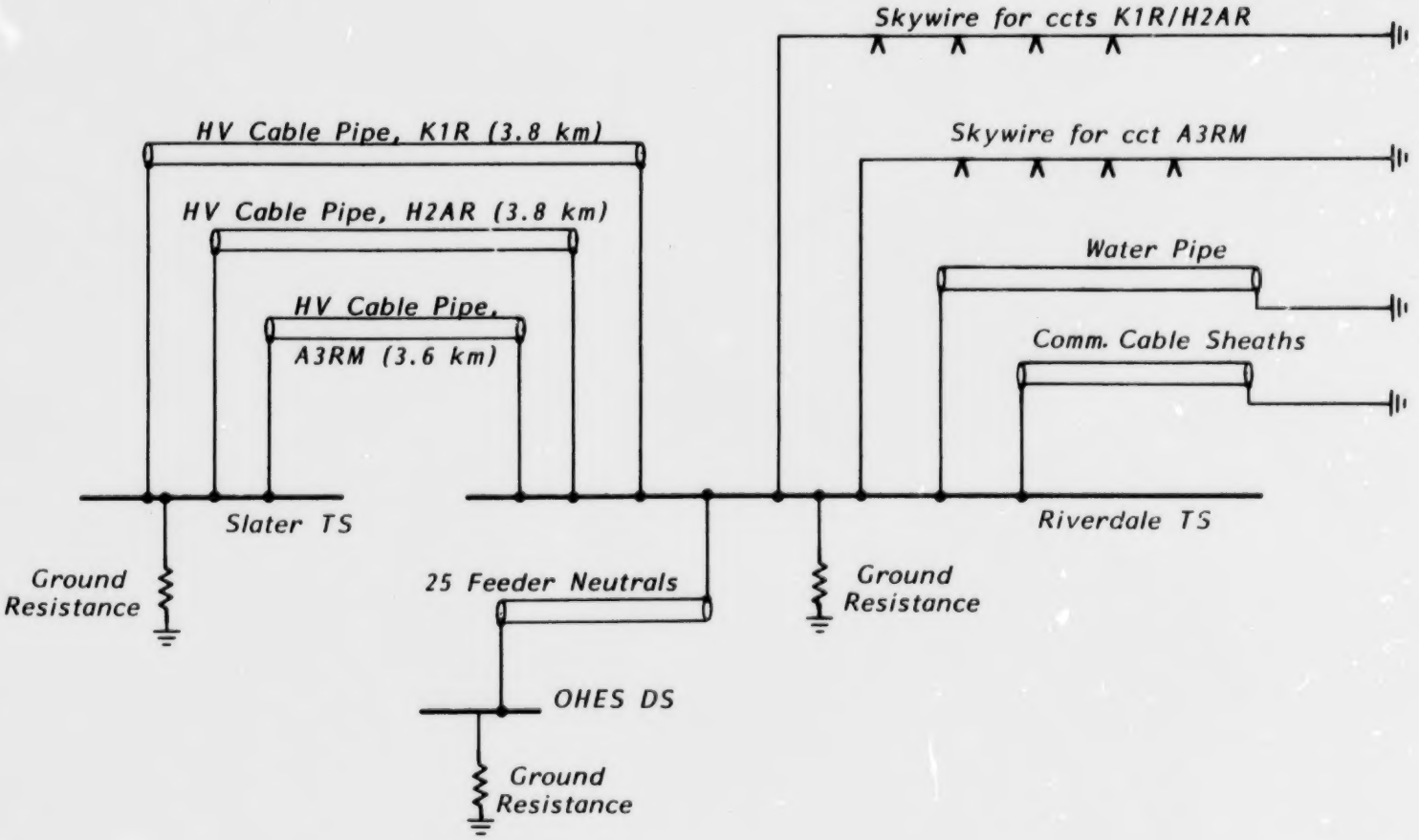

FIGURE 3

OTTAWA RIVERDALE TS
GROUNDING SYSTEM INTERCONNECTIONS

174394-RD

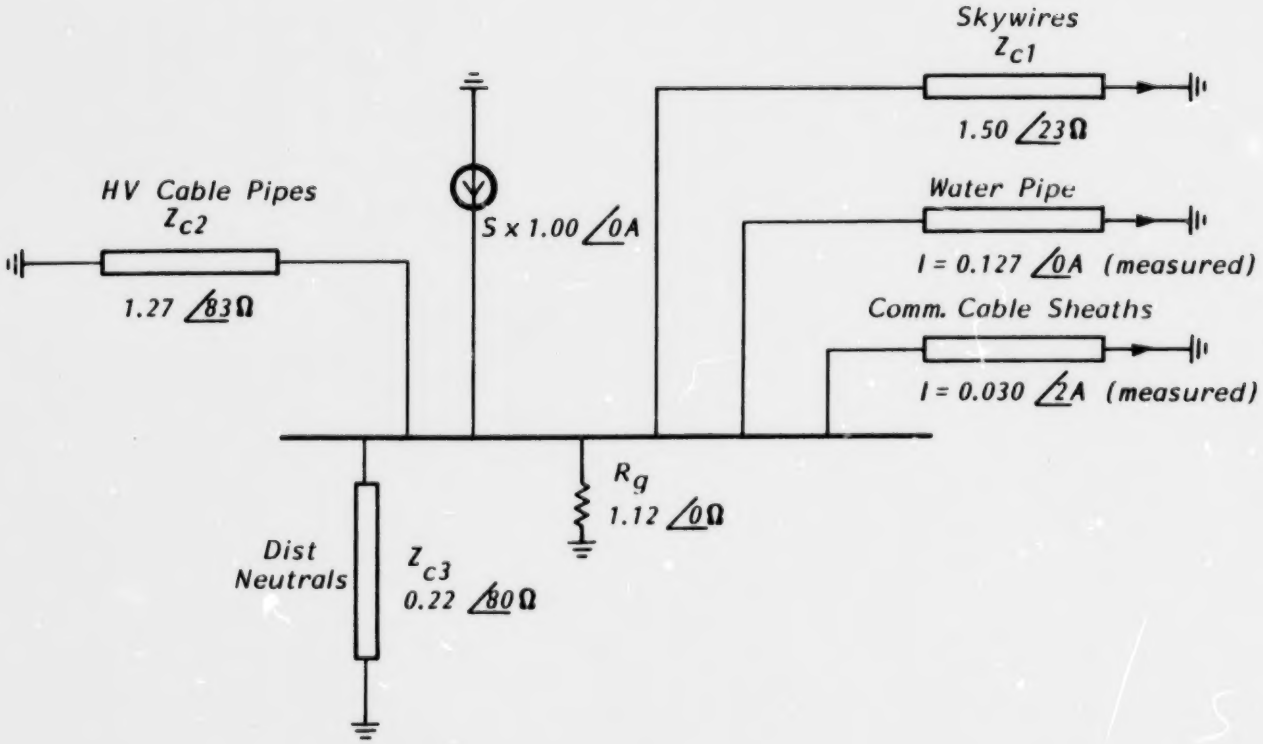

FIGURE 4

OTTAWA RIVERDALE TS
CONDUCTIVE EQUIVALENT CIRCUIT FOR HV STATION FAULT

174395-RD

APPENDIX A
SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \quad (\Omega/km) \tag{1}$$

$$R_s = 0.059 + R_{ac} \quad (\Omega/km) \tag{2}$$

$$X_s = 0.0377 \ln \left(\frac{8440\ \rho_s}{GMR^2}\right) \quad (\Omega/km) \tag{3}$$

Where, R_{ac} = conductor ac resistance (Ω/km)
ρ_s = soil resistivity (Ω.m)
GMR = conductor geometric mean radius (m)

For pipes or shields, R_{ac} and X_{ac} (conductor internal reactance added to X_s) are calculated as shown in reference/3/.

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \quad (\Omega/km) \tag{4}$$

$$R_m = 0.0377 \tan^{-1} \left(\frac{8440\ \rho_s}{GMD^2}\right) \quad (\Omega/km) \tag{5}$$

$$X_m = 0.0377 \ln \left(\frac{8440\ \rho_s}{GMD^2} + 1\right) \quad (\Omega/km) \tag{6}$$

Where, ρ_s = soil resistivity (Ω.m)
GMD = geometric mean distance between conductors (m)

3. Tower Footing Resistance, R_t

$$R_t = \frac{\rho_s}{2\pi}\left[\frac{1}{r} + \frac{2.707}{w}\right] \ (\Omega) \qquad (7)$$

Where, ρ_s = soil resistivity (Ω.m)
r = equivalent footing radius (m)
w = footing spacing (m)

4. Chain Impedance of Skywires, Z_c

$$Z_c = \sqrt{Z_s \ell R_t} \ (\Omega) \qquad (8)$$

Where, Z_s = conductor earth return self impedance (Ω/km)
ℓ = span length (km)
R_t = tower footing resistance (Ω)

5. Station Earth Potential to Remote Ground $V_{(x)}$

Refer to /5/.

For disk-like electrode in uniform earth,

$$V_{(x)} = \frac{\rho_s I_g}{2\pi r} \sin^{-1}\left(\frac{r}{x}\right) \qquad (9)$$

Where, ρ_s = soil resistivity (Ω.m)
I_g = ground current (A)
r = station radius (m)
x = distance from station centre (m)

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